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EVALUATION OF TOOL LIFE - TOOL WEAR IN MILLING OF INCONEL 718 SUPERALLOY AND THE INVESTIGATION OF EFFECTS OF CUTTING PARAMETERS ON SURFACE ROUGHNESS WITH TAGUCHI METHOD

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Original scientific paper
In this study, the effects of cutting speed, milling direction (down milling, up milling), coating layer (TiAlN and TiAlN-TiN) and the number of inserts of tool holder on the surface roughness and tool life in dry milling of Inconel 718 superalloy were investigated. In the first place, the effects of control factors on the tool life were studied at the cutting speeds of v = 50 m/min and v = 100 m/min. The alternation of flank wear depending on the cutting time was examined. The types of wear and wear mechanisms were determined by examining the optical images of worn tools. In the second part of the study, for the purpose of investigating the effects of control factors on the surface roughness, L16 Taguchi Technique was used and the optimal control factor levels, giving the lowest value of the average surface roughness parameter (*Ra*) were determined. The effect of cutting speed on the tool life was more than the effects of the milling type and number of inserts. Down milling resulted in longer tool life compared to up milling method. In up milling, longer tool life was obtained with 2 inserts at low cutting speeds and with 4 inserts at high cutting speeds. TiAlN-TiN coated tools exhibited twice as long tool life than the TiAlN coated tools. For both milling methods, the most effective wear types were flank wear and nose wear.

Keywords: *coated carbide tools, Inconel 718, surface roughness, tool life, up/down milling*

Procjena radnog vijeka alata - trošenja alata kod glodanja superlegure Inconel 718 i istraživanje učinaka parametara rezanja na hrapavost površine kod Taguchi metode

Izvorni znanstveni članak
U ovom se radu istraživalo djelovanje brzine rezanja, smjera glodanja (prema dolje, prema gore), sloja premaza (TiAlN i TiAlN-TiN) i broja umetaka držača alata na površinsku hrapavost i trajanje alata kod suhog glodanja superlegure Inconel 718. U prvom su se redu proučavali učinci kontroliranih faktora na radni vijek alata pri brzinama rezanja od v = 50 m/min i v = 100 m/min. Ispitivala se promjena površinskog trošenja ovisno o brzini rezanja. Tipovi trošenja i mehanizmi trošenja su se određivali ispitivanjem optičkih slika istrošenih alata. U drugom dijelu rada, kako bi se istražilo djelovanje kontrolnih faktora na hrapavost površine, primijenjena je L16 Taguchi metoda te su određeni optimalni nivoi kontrolnih faktora, dajući najnižu vrijednost prosječnog parametra hrapavosti površine (*Ra*). Brzina rezanja je imala veći učinak na vijek trajanja alata nego što su to imali način glodanja i broj umetaka. Glodanje prema dolje je rezultiralo duljim trajanjem alata u usporedbi s glodanjem prema gore. Kod glodanja prema gore dulji radni vijek alata je postignut s 2 umetka pri malim brzinama rezanja, a s 4 umetka pri velikim brzinama rezanja. Pokazalo se da alati obloženi TiAlN-TiN premazom imaju dvostruko dulji radni vijek nego alati obloženi TiAlN premazom. Kod obje metode glodanja najučinkovitije vrste trošenja bile su površinsko trošenje i trošenje vrha alata.

Ključne riječi: *alati premazani karbidima, Inconel 718, hrapavost površine, radni vijek alata, glodanje prema gore/prema dolje*

1 Introduction

Machinability can be expressed as the easiness or difficulty in a machining operation involving cutting conditions such as cutting speed, feed rate and depth of cut. The machinability of a material can be defined by measuring the tool life, surface roughness and cutting force. The machinability of superalloy materials is much more difficult compared to steels and stainless steels [1-6].

High temperature alloys or superalloys have better strength-weight ratio and higher heat and corrosion resistance compared to conventional alloys. Superalloys are preferred in certain industries such as space, turbine and furnace accessories, transportation of chemicals and oil refinery, due to their better performance. All of these applications are realized under different temperatures and pressures, so the materials to be used under these conditions should not loose their characteristics [7, 8]. Superalloys have different structure and characteristics and are generally classified into four classes. Nickel base alloys form the largest part of alloys, but they are very difficult to process [1, 9 ÷ 11]. They usually consist of 38 ÷ 76 % nickel (Ni), more than 27 % chromium (Cr) and 20 % cobalt (Co) [2]. These materials are used where high corrosion resistance and high temperature properties are needed [9, 10, 12 ÷ 16]. Inconel 718 is a widely used nickel base superalloy and approximately 25 ÷ 40 % of it is being converted into several products through casting. The rest is processed by machining. Thus, for the last 30 years, Inconel 718 has been very important in the research studies for nickel base superalloys [2, 5, 6].

Nickel-based superalloys currently have hard abrasive carbides in the microstructure (e.g. MC, M23C6) that allow the formation of abrasive wear, which causes the formation of tool wear. The austenitic matrix used for machining nickel-based superalloys leads to rapid hardening. It is the main reason behind the abrasion along the cutting depth line [2]. High dynamic shearing strength during the cutting process results in localized shearing stresses and an abrasive saw tooth profile, which notches the cutting tools during titanium alloy machining. Because of the high strength and hardness properties at high temperatures, cutting tools undergo deformation due to the cutting process [7]. For these reasons, specially designed tool materials, geometry and cutting conditions are used in cutting process. High cutting power and high temperature combinations cause tool deformation and cracks along the edge of the cutting tool during machining. Additionally, hot hardness usually occurs quickly in these tools. During the processing, a hardened surface may occur due to the depth of the cutting line of the tool and affect the accuracy of the fatigue strength and geometry [9, 10, 12 ÷ 14, 17 ÷ 19]. A low thermal diffusion force, which has a high thermal trend in tool nose cutting temperatures (≥ 1000 °C), is pioneered in regionalization. The workpiece material formed by welding from the cutting edge of the tool is not constantly adhered to the BUE (Built-Up-Edge), and the formation is caused by the deterioration of machined surfaces.

Cemented carbides and mixed based cemented carbides are also widely used in the machining of nickel base superalloys and titanium alloys. Cemented carbides contain 6 % cobalt and 94 % WC (tungsten carbide) and the Co mixture ratio is between 5 % and 12 % whereas mixed carbide inserts contain TiC (titanium carbide), TaC (tantalum carbide) or NbC (niobium carbide). Coating materials such as TiC (titanium carbide), TiN (titanium nitride) and Al_2O_3 (aluminium oxide) improve existing characteristics of the carbide tools. In the machining operation of these superalloys different cutting tool qualities exhibit different performances. The machinability performances of these materials are increased by selecting appropriate cutting operations, different cooling systems, determination of optimum cutting parameters to give the longest tool life, definition of tool wear mechanism and measurement of cutting forces. Studies show that the machinability performances of these superalloys improved considerably [4].

In this study, the effects of milling direction (*MD*), coating layer/cutting tool (*CT*), insert number (*IN*) and cutting speed (v) on the tool life (T) and surface roughness (Ra) in the dry milling of Inconel 718 superalloy materials were investigated.

2 Experimental study

2.1 Workpiece material

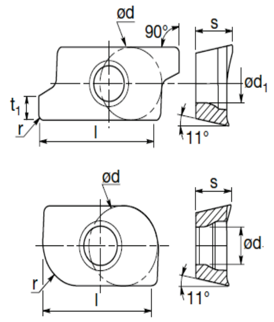
The workpiece that was used in the machinability tests Inconel 718 is a nickel base superalloy. The dimensions of the workpiece are 100 × 100 × 200 mm (2,52" × 3,937" × 7,854"). As it is seen from Tab. 1, Inconel 718 superalloy contains considerable amounts of nickel, iron, chrome and lower amounts of niobium, molybdenum, titanium and aluminium. The hardness of the workpiece is C029, its yield strength is 100 ksi (690 MPa), its tensile strength is 152 ksi (1048 MPa), and its elongation is 36,0 % [20].

Table 1 Chemical composition of Inconel 718 - % volume [20]

C	Mn	P	S
0,051	0,071	0,08	0,0002
Si	Ni	Cr	Mo
0,093	51,92	18,36	2,91
Co	Cu	Ti	Cb
0,16	0,040	1,00	5,03
Al	B	Fe	Ta
0,54	0,003	19,78	0,008

2.2 Cutting tools

In the machinability tests, RT160608 ER-81 2003 S05 (S01-S10-Safety Company) coded and TiAlN coated (by PVD method) carbide tools were used (Fig. 1). These cutting tools provide excellent wear resistance and are used in the finish cutting and semi-finish cutting of steel, hard materials, stainless steels and heat resisting alloys. They may also be used in the finishing of cast irons. In the milling operation of nickel and cobalt based superalloys of Hastelloy, Inconel, Stellite the cutting speed and feed per tooth (f_t) for 15 minutes of tool life are v = 50 m/min and f_t = 0,10 mm/tooth as suggested by the manufacturer [21]. Another cutting tool used in the machinability operation is RT160608 ER-11 5020 S15 (S10-S20) coded tool, belonging to the same company, and having micro particle carbide quality and TiAlN-TiN coated (by PVD method) which is multi-purposed and provides a good stability between wear resistance and toughness (Fig. 1). These tools are also used in the finishing and rough machining operations of steels, stainless steels, heat resisting alloys and titanium alloys. In the machining of the same materials with the RT160608 ER-11 5020 S15 (S10-S20) coded tools, the cutting speed is v = 80 m/min, and the feed rate is f_t = 0,10 mm/tooth [21]. The geometries of the cutting tools which were used in the tests are shown in Fig. 1. A BT-40 / RT 16 tool holder of 50 mm diameter with 5 cutting inserts was used.



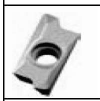
a) RT160608 ER-11 5020							
	*d*	*s*	d_1	*l*	*r*	b_s	t_1
	9,30	6,42	4,7	18,00	0,8	-	3,30
b) RT160608 ER-81 2003							
	*d*	*s*	d_1	*l*	*r*	b_s	t_1
	9,30	6,40	4,7	18,00	0,8	-	2,90

Figure 1 The inserts used in the experiments [21] (dimensions in mm)

2.3 Machine tool

In machining tests, three axis AWEA AV-610 CNC milling machine (P = 7,5 kW, n = 8000 rpm) was used.

2.4 Experimental procedure

Machinability tests were carried out for two different milling directions (down and up milling). The experimental design used in the tool life and surface roughness tests and the results of the tests are shown in Tab. 2. In the machining tests, the depth of cut and the feed per tooth were taken as d = 1,0 mm and f_t = 0,05 mm/tooth, respectively. The cutting speeds were taken as v = 50 m/min and v = 100 m/min and, the spindle speeds as n_1 = 319 rpm and n_2 = 637 rpm. As shown in Fig. 2, the cutting tool feed direction was along the y-axis and the machining was made along the width (B) of B = 100 mm and the cutting width (w) was chosen as w = 10 mm. The machining tests were made under dry cutting conditions.

In the surface roughness tests, Time TR200 (cut-off distance 0,8 mm) portable surface roughness device was used, and 5 measurements were made from the machined surfaces and the arithmetic mean of the results was taken. When measuring, the stylus moved perpendicular to the traces on the machined surface. New inserts were used in each test. In the tool life tests, for the purpose of measuring the flank wear depending on the machining time, a three-axis (x-y-z axes) vernier scaled optical microscope of 0,005 mm accuracy and 5-100× magnification was used. The flank wear criterion (V_B) was taken as V_B = 0,3 mm. An optical microscope with a digital camera was used to determine the wear types on the worn inserts.

In the down milling, the formation of the maximum chip thickness occurs at the point where the cutting insert touches the workpiece. The chip thickness decreases as the cutting tool rotates. As shown in Fig. 2, in the machinability tests of down milling operations, the enter angle of the tooth starts from the x-axis, and is calculated as below [22].

$$\varphi_{\text{Enter}} = 90° + \arcsin\frac{r-w}{r} = 90° + \arcsin\frac{25-10}{25} = 127°. \quad (1)$$

The angle of exit after the active cutting zone of the tooth (the point where the chip removes the workpiece) is approximately 180° (φ_{Exit}=180°) and the thickness of the chip is 0 mm at the exit point. As seen from the same figure the enter angle is 0° (φ_{Exit}=0°) for the up-milling. At the beginning, when the insert touches the workpiece the chip is thinner, but the chip thickness increases as the cutting insert rotates. The chip thickness reaches the maximum value at the point where the cutting insert leaves the workpiece. The exit angle of cutting insert when leaving the workpiece is calculated to be 53° (φ'_{Exit}=53°) [22].

$$\varphi'_{\text{Exit}} = \arccos\frac{r-w}{r} = \arccos\frac{25-10}{25} = 53°. \quad (2)$$

In down and up milling, tool holder starts to cut from a point at the edge of the workpiece to the centre of the tool holder and at a position created in a vertical distance to the feed direction. This distance (L_1);

$$L_1 = \sqrt{r^2-(r-w)^2} = \sqrt{25^2-(25-10)^2} \cong 20\,\text{mm}, \quad (3)$$

was calculated to be $L_1 \cong$ 20 mm [22]. Machining operation continues along the direction of tool holder center from one edge of the workpiece to the other edge and workpiece widthwise vertically. From here the machining (ML) is found as follows [22]:

$$ML = L + L_1 = 100 + 20 = 120. \quad (4)$$

The cutting time for only one machining length (t_1) at n_1 = 319 rev/min spindle revolution is calculated to be t_1 = 225,733 s [22]. For n_1 = 637 rpm is t_2 =113 s. Besides, the time values read on the machining centre and the calculated time values during machining were verified.

$$t_1 = \frac{ML/(f_t \cdot z)}{n_1/60} = \frac{120/(0{,}05 \cdot 2)}{319/60} = 225{,}733\,\text{s}. \quad (5)$$

Table 2 Experimental design and results for tool life and surface roughness [20]

a) Tool life tests

Test No.	Cutting speed	Milling direction	Insert number	Cutting tool	Tool life	Tool life
	v / m/min	MD	IN, (number)	CT	T / min	T / s
1	50	Down Milling	2	TiAlN-TiN	19,866	1192
2	100	Down Milling	2	TiAlN-TiN	1,500	90
3	50	Up Milling	2	TiAlN-TiN	1,666	100
4	100	Up Milling	2	TiAlN-TiN	0,416	25
5	50	Down Milling	2	TiAlN	11,133	668
6	50	Down Milling	4	TiAlN	2,633	158
7	100	Down Milling	2	TiAlN	0,666	40
8	100	Down Milling	4	TiAlN	1,666	100

b) Surface roughness tests

Test No.	Cutting speed	Milling direction	Insert number	Cutting tool	Surface roughness Ra / μm					
	v / m/min	MD	IN, (number)	CT	Ra_1	Ra_2	Ra_3	Ra_4	Ra_5	Ra_ave
1	50	Down Milling	2	TiAlN-TiN	0,222	0,190	0,182	0,193	0,220	0,201
2	50	Down Milling	2	TiAlN	0,220	0,182	0,190	0,181	0,196	0,193
3	50	Up Milling	4	TiAlN-TiN	0,326	0,358	0,324	0,378	0,341	0,345
4	50	Up Milling	4	TiAlN	0,373	0,339	0,312	0,299	0,268	0,318
5	50	Down	4	TiAlN-TiN	0,279	0,282	0,300	0,230	0,229	0,264
6	50	Down	4	TiAlN	0,638	0,537	0,670	0,527	0,633	0,601
7	50	Up Milling	2	TiAlN-TiN	0,151	0,138	0,169	0,174	0,159	0,158
8	50	Up Milling	2	TiAlN	0,497	0,525	0,528	0,510	0,456	0,503
9	100	Down	4	TiAlN-TiN	0,199	0,152	0,187	0,173	0,189	0,180
10	100	Down	4	TiAlN	0,584	0,633	0,680	0,579	0,585	0,612
11	100	Up Milling	2	TiAlN-TiN	0,332	0,303	0,299	0,443	0,324	0,340
12	100	Up Milling	2	TiAlN	0,171	0,185	0,178	0,179	0,180	0,178
13	100	Down	2	TiAlN-TiN	0,126	0,130	0,104	0,109	0,122	0,118
14	100	Down	2	TiAlN	0,438	0,480	0,413	0,359	0,421	0,422
15	100	Up Milling	4	TiAlN-TiN	0,203	0,194	0,204	0,211	0,202	0,202
16	100	Up Milling	4	TiAlN	0,734	0,813	0,695	0,691	0,786	0,743

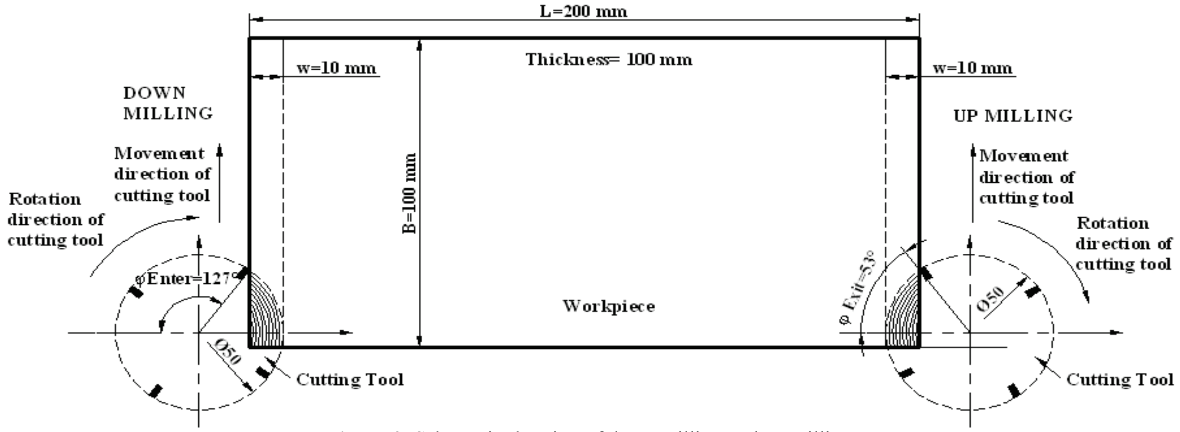


Figure 2 Schematic-drawing of down milling and up milling

3 Results and discussion
3.1 Tool life-flank wear

In the surface milling of Inconel 718 superalloy, formation of flank wear depending on the cutting time is given in Figs. 3 ÷ 5. Machining time vs. flank wear curves were given to determine the effects of milling method, number of inserts and cutting tool coating material at different cutting speeds. When measuring flank wear, the flank wear criterion was taken as V_B = 0,3 mm. Because, in the previous tests, especially at high cutting speed (v = 100 m/min), after V_B = 0,3 mm, tools were observed to be worn out rapidly and lost tool life. To determine the effects of the milling direction on flank wear, in machinability tests under cutting conditions with PVD-TiAlN–TiN coated carbide inserts (f_t = 0,05 mm/tooth, d = 1,0 mm), at both the two cutting speeds of v = 50 m/min and v = 100 m/min the machining time was observed to be fairly short, and in approximately 30 s, the V_B = 0,3 mm criterion was reached (Fig. 3). An 1192 s machining time (about 20 min) was obtained by down milling at a 50 m/min cutting speed. Under the same cutting conditions, when the cutting speed was increased to 100 m/min the flank wear increased rapidly and at T = 90 s the V_B criterion was reached (Fig. 3, Tab. 2). In this study, the cutting times obtained at cutting speeds of v = 50 m/min and v = 100 m/min verify the reality of the highest cutting speed of v = 50 ÷ 60 m/min for the milling which was suggested by researchers on different studies on the machinability of Inconel 718.

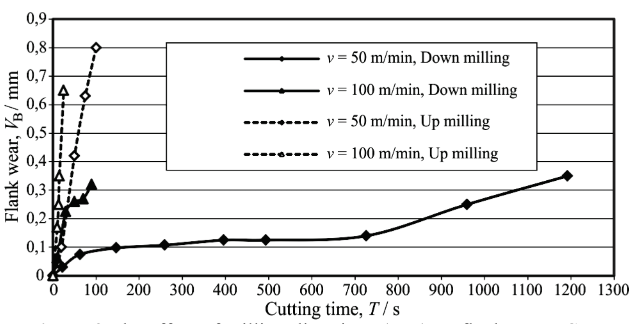


Figure 3 The effect of milling directions (*MD*) on flank wear, *CT* = PVD – TiAlN-TiN, *IN* = 2, f_t = 0,05 mm/tooth, d = 1,0 mm

However, in this study, performances at high cutting speeds were tested by increasing the suggested cutting speeds. Apart from the known effect of cutting speed on tool wear and tool life, the effect of the milling method was also determined. A longer tool life can be obtained by down milling, as shown in Fig. 3 regardless of cutting speed.

Up milling was made by using PVD-TiAlN coated carbide inserts under the cutting conditions of f_t = 0,05 mm/tooth and d = 1,0 mm and the effect of number of inserts on the tool holder was investigated by measuring the flank wear depending on the cutting time.

Fig. 4 shows the significant effect of the cutting speed and the effect of insert number in cuttings with 2 and 4 inserts at two different cutting speeds. Regardless of the insert number, a shorter tool life was obtained at high cutting speeds. However, by milling with 4 inserts at v = 50 m/min cutting speed, V_B = 0,3 mm criterion was reached in T = 120 s of cutting time, whereas by milling with 2 inserts it was reached in T = 530 s and 4,4 times more machining time was obtained. When milling with 4 inserts at v = 100 m/min, this ratio was approximately two times and in favor of the milling made. Therefore, when milling at higher cutting speeds, as the number of inserts on the tool holder increased, the necessary cutting time to reach the V_B = 0,3 mm criterion increased (Fig. 5). At a high cutting speed, the longer tool life obtained by milling with 4 inserts rather than with 2 inserts can be explained as follows: in the cutting at constant feed rate the turning chip amount per 4 inserts was lower compared to the milling with 2 inserts. As the chip removal volume decreases during cutting, the forces falling on the cutting tool will also decrease.

In Fig. 6, the effect of the cutting tool coating material (*CT*) on the formation of flank wear depending on the machining time was investigated. When milling at a v = 50 m/min cutting speed, TiAlN-TiN coated tools showed twice as longer tool life than TiAlN coated tools. In both machining with two different tools, a rapid flank wear occurred up to V_B = 0,07 mm, and the tool wear increased almost linearly with TiAlN coated tools depending on the machining time. Whereas with the TiAlN-TiN coated tools, after the V_B = 0,07 mm criterion, V_B = 0,140 mm was achieved in approximately 730 s of milling and after this V_B value a linear and fast growing wear occurred depending on the machining time. In the milling of Inconel 718, a tool life under T = 100 s was achieved with both of the coating material at v = 100 m/min cutting speed. The flank wear criterion was exceeded under a cutting time of T = 100 s. The contribution of TiAlN-TiN coated tools to the increasing machining time was due to the decreasing frictional coefficient between the tool and chip interface by the last TiN coating layer during machining.

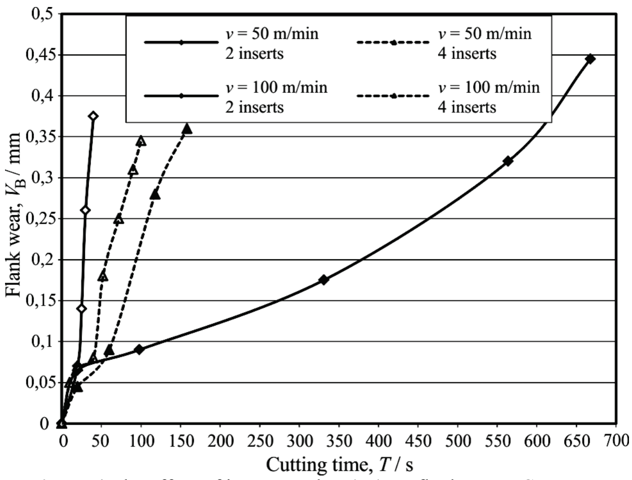


Figure 4 The effect of insert number (*IN*) on flank wear, *CT*=PVD-TiAlN, *MD* = Up milling, f_t = 0,05 mm/tooth, d = 1,0 mm

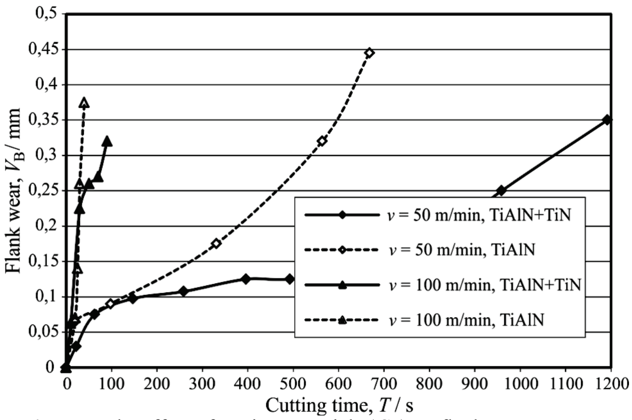
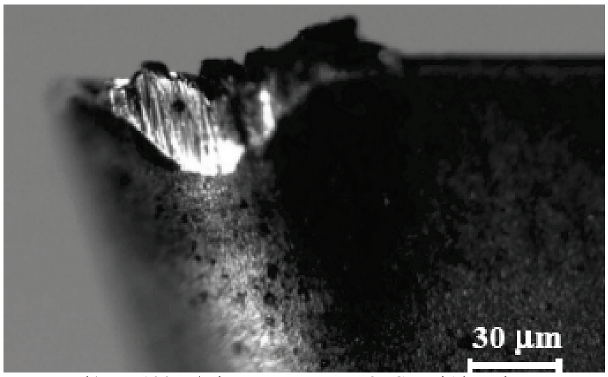


Figure 5 The effect of cutting materials (*CT*) on flank wear, *MD*=Up milling, *IN* = 2, f_t = 0,05 mm/tooth, d = 1,0 mm

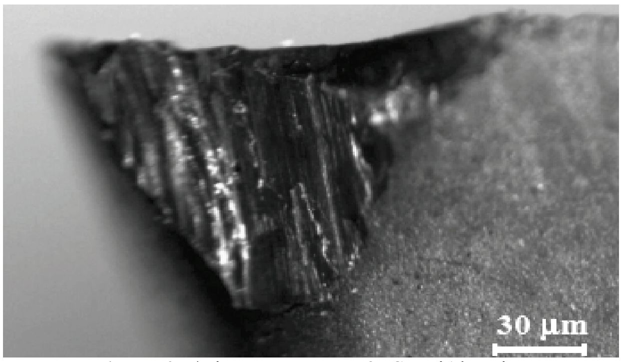
3.2 Observation of tool wear

In this study for the machining of nickel base super alloys, PVD coated tools were preferred. In Fig. 6 and Fig. 7, optical microscope images of flank wears in the milling of Inconel 718 super alloy at constant cutting conditions of different cutting speed, different milling direction, different number of inserts, f_t = 0,05 mm/tooth and d = 1,0 mm were given. In Figs. 6a ÷ 6d, flank wear images in the milling with TiAlN-TiN tools (using 2 inserts), in the down and up milling at lower (v = 50 m/min) and higher (v = 100 m/min) speeds were shown. In Figs. 6a and 6b, a non-uniform flank wear, as a result of down milling was given. Especially, with the increasing of cutting speed this non-uniform structure increased too (Fig. 6). Due to high temperature at high cutting speed the molten workpiece material diffused to the area where the chip depth terminated (Fig. 6b). In the up milling, cutting edge deteriorated in the flank wear zone, coating layers got worn and reached the main material of the cutting tool and the progressing of tool wear was more rapid (Figs. 6c and 6d) [22]. In the TiN/AlTiN coated tools, among the different wear types, the first noticeable wear was nose wear and chippings on the cutting edge. The notching at the cutting depth caused by high temperature, high workpiece resistance and abrasive chips also created machining problems [23].

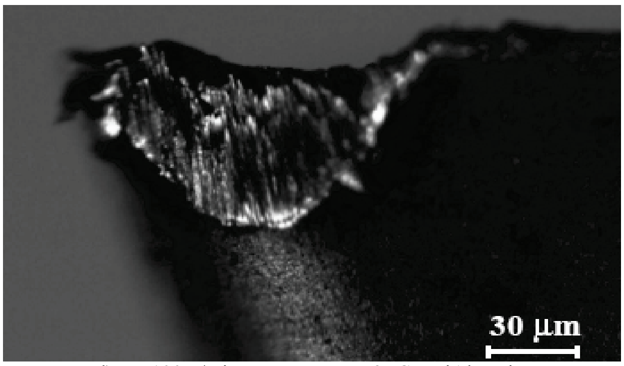
a) v = 50 m/min, *MD*=DM, *IN*=2, *CT*=TiAlN-TiN



b) v = 100 m/min, *MD*=DM, *IN*=2, *CT*=TiAlN-TiN



c) v = 50m/min, *MD*=UM, *IN*=2, *CT*=TiAlN-TiN



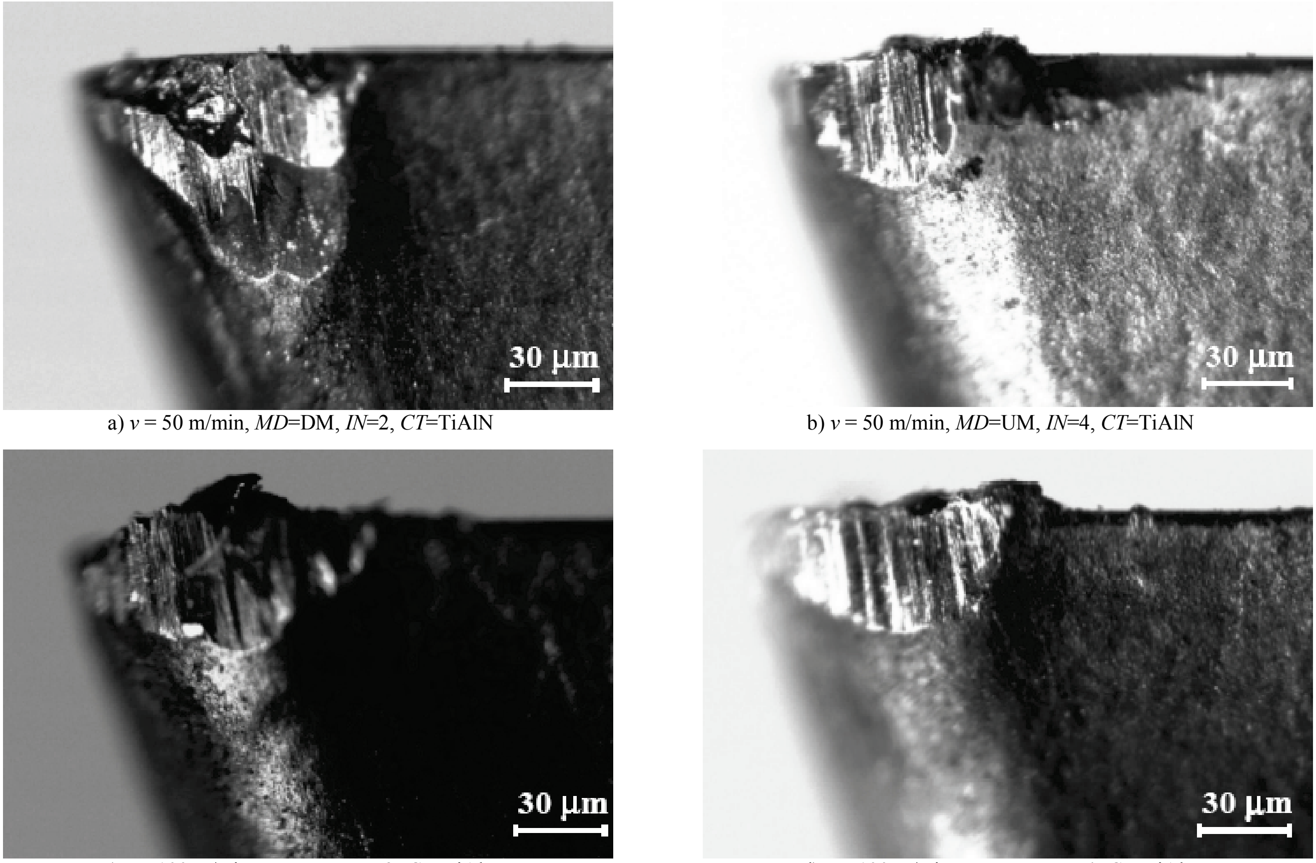
d) v = 100m/min, *MD*=UM, *IN*=2, *CT*=TiAlN-TiN

Figure 6 Optical microscope images of flank wear; the effect of milling direction (*MD*), f_t = 0,05 mm/tooth, d = 1,0 mm

In this milling study, the effective wear for both of the milling methods was free surface wear and nose wear. In both of the milling wear increased linearly depending on the cutting time [22]. Because of the irregular and increasing tool wear created in the up milling operations, contributions of TiN layer on the cutting tool performance came out to be insufficient.

In Figs. 7a ÷ 7d, in the down milling with TiAlN coated tools, the flank wear images in the milling with 2 and 4 inserts at lower and higher cutting speeds (v = 50 m/min and v = 100 m/min) are given. It is seen from Fig. 3 that tool life obtained with the down milling is higher as it was specified earlier.

In Figs. 7a and 7b, the images of worn tools as a result of milling with 2 and 4 inserts at lower cutting speed are given. As seen from Fig. 7b a regular flank wear was obtained in milling with 4 inserts but the workpiece material adhered to the cutting zone at the point where the chip depth terminated, whereas in Fig. 7a an irregular flank wear is observed in milling with 2 inserts and bulky chippings created towards the nose of cutting tool. In Fig. 7c, in the milling with 2 inserts, combination of crater wear and nose wear are seen due to the effect of high cutting speed. Melting of the nose of the tool by wearing due to high temperature at a high cutting speed is observed. Again, molten workpiece diffused to the cutting edge due to the high temperature during cutting. Whereas in the milling with 4 inserts, despite the high cutting speed a regular flan wear occurred, the depths and widths of wear tracks increased by the effect of hard particles inside workpiece (Fig. 7d). Cutting edge deformed and the melted workpiece diffused.



a) v = 50 m/min, *MD*=DM, *IN*=2, *CT*=TiAlN

b) v = 50 m/min, *MD*=UM, *IN*=4, *CT*=TiAlN

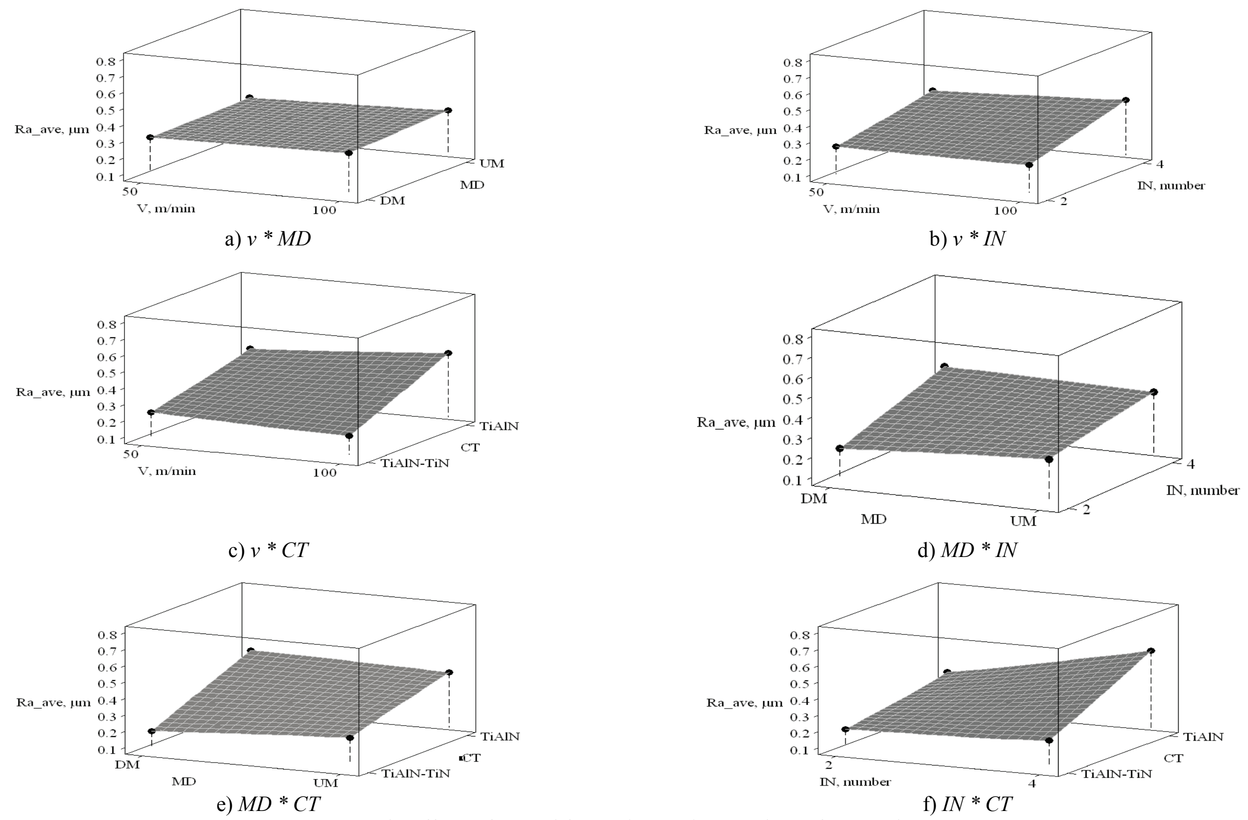
c) v = 100 m/min, *MD*=DM, *IN*=2, *CT*=TiAlN

d) v = 100 m/min, *MD*=UM, *IN*=4, *CT*=TiAlN

Figure 7 Optical microscope images of flank wear on cutting tools; the effect of insert number (*IN*), f_t = 0,05 mm/tooth, d = 1,0 mm

3.3 The effects of control factors on surface roughness

In the surface milling of Inconel 718 nickel base super alloy at constant feed rate and chip depth with coated carbide tools having different coating layers, measurements taken from the machined samples to determine the effect cutting speed, milling direction and number of cutting inserts on the surface roughness, are given in Tab. 2. In the surface milling of Inconel 718 with carbide tools, three dimensional (3D) interaction graphs showing the development of the surface roughness of workpiece depending on the cutting speed, milling direction, number of inserts and cutting tool coating layer control parameters are given in Fig. 8. In Fig. 8a the effect of interaction of cutting speed and milling direction on the surface roughness is given. In the graph, surface roughness got worse depending on the increasing of cutting speed but the milling direction did not affect the increasing of surface roughness. It is also seen that cutting speed has no significant effect on the increase in surface roughness. In Fig. 8b, the effect of interaction of cutting speed-number of inserts on the surface roughness is given. In this interaction while the effect of cutting speed is not seen, the effect of number of inserts on the surface roughness is clearly seen. As the number of inserts on the tool holder increases, surface roughness increases too. In the study of Dilipak and Gezgin [24], in the milling of AISI D3 steel, the increase of *Ra* value depending on the increase of number of inserts was contributed to the vibration between the cutting tool and workpiece and the friction of chips (from the cutting operation) to the workpiece. In the same study, it was also stated that the vibration between the cutting tool and the workpiece would be realized at higher frequency with the increasing of number of inserts. On the other hand, as seen from the schematic demonstration, in the down and up milling, a higher surface roughness value may be obtained because the number of tracks caused by the inserts on the surface during machining may be more in the milling with 4 inserts. It is seen from Fig. 8b that the surface roughness in machining at v = 100 m/min and with 4 inserts is relatively high. This can be contributed to the increasing of number of revolutions depending on the cutting speed and increasing of number of inserts which is in contact with machined surface with the increasing of number revolutions. The effect of interaction of cutting speed and cutting tool is given in Fig. 8c. In this figure, the superiority of TiAlN-TiN coated carbide tool in providing lower surface roughness is seen. Especially, at the v = 100 m/min high cutting speed lower surface roughness values were obtained. At both cutting speeds, the TiAlN-TiN coated tools exhibited better performances than the TiAlN coated tools. Especially, at high cutting speeds the lower performance of TiAlN coated tools is clearly seen from the same figure. The high performance of TiAlN-TiN coated carbide tools arises from the lower factor of friction provided by the TiN layer. Due to the easy chip flow the cut chips pile up on the tool cutting edge and this way there is no delay in the natural tool wear time, the geometry of the cutting tool nose radius creating the shape of the tracks on the machined surface does not spoil and the chips move away from the cutting area. These favorable contributions end up with lower surface roughness values. The effect of milling direction and the number of inserts on the surface roughness is given in Figure 8.d. As seen from the figure, there is no significant effect of number of cutting inserts on the surface roughness in up milling but in down milling surface roughness values are getting worse as the number of inserts increases. In the down milling, lower surface roughness values were obtained with few numbers of inserts. The interaction of milling direction and cutting tool on the surface roughness is seen in Fig. 8e. Lower surface roughness values are obtained with TiAlN-TiN coated tools using especially down milling. Finally, the interaction of number of inserts and cutting tool is given in Fig. 8f. It is observed from the figure that surface roughness gets better with low number of inserts by using TiAlN-TiN coated tool.



a) v * MD b) v * IN c) v * CT d) MD * IN e) MD * CT f) IN * CT

Figure 8 The effects of control factors interactions on the surface roughness

The main-effect graphics showing the effects of control factors on the surface roughness are given in Fig. 9. The differences between the surface roughness values obtained at different levels of each control factor were used to list the control factors in order of effectiveness.

According to this list, the cutting tool (CT), the number of inserts (NI), the milling direction (MD), and the cutting speed (v) are the most influential factors on the surface roughness, respectively. While the cutting tool and the number of inserts have a significant effect on the surface roughness, the cutting speed and the milling direction do not have an important effect on the surface roughness. The optimal levels of the control factors that will give the lowest average surface roughness value (Ra_ave) in the machining of nickel based superalloy Inconel 718 with coated carbide tools are as follows:

- Cutting speed (v): 50 m/min
- Milling direction (MD): Down milling
- Number of inserts (NI): 2 inserts
- Cutting Tool (CT): TiAlN-TiN coated tool.

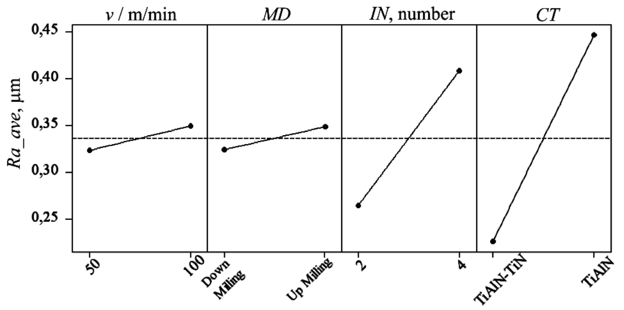


Figure 9 Main-effect graphic showing the effect of control factors on the surface roughness

The percentage effects of the control factors on the improvement of *Ra* surface roughness in milling of nickel-based superalloy Inconel 718 are given in Tab. 3. The average percentage contributions of the control factors given in Tab. 3 were obtained by using the experimental results for the surface roughness shown in Tab. 2 which were obtained by comparing the *Ra* average results at two levels of each control factor and by taking the average of these comparison results. Tab. 3 shows that the cutting tool is the most influential factor on surface roughness. When using TiAlN-TiN coated tools in the machining of Inconel 718 with TiAlN-TiN and TiAlN coated carbide tools they provide 131,50 % contribution to the improvement of surface roughness. The secondary effect is created by the number of inserts to be attached to the tool holder. The surface roughness improves at the rate of 57,25 % when the number of inserts is two. When the workpiece is machined by down milling, the obtained surface roughness *Ra* values are 38,76 % lower. While the lowest effect is provided by the cutting speed the Ra surface roughness values obtained at low cutting speed (v = 50 m/min) are 23,7 % which is lower than those obtained at high cutting speed (v = 100 m/min). In the study carried out by Dilipak and Gezgin, the surface quality decreased by 6 ÷ 10 % when the cutting speed increased by 50 % in the milling of AISI D3 cold work tool steel supporting the results of this study [24]. In the same study, increasing the number of inserts from 1 to 6, decreased the surface quality by 172 %, and the most influential parameters on the surface quality became the number of cutting inserts, the feed rate and the cutting speed, respectively.

Table 3 Control factors contributions to the improvement of surface roughness

a) The contribution of cutting speed

Test No.	Test conditions	*Ra* obtained v = 50 m/min, (µm)	*Ra* obtained v = 100 m/min, (µm)	Contribution to improvement at *Ra* average (%)
1*13	MD= DM, IN= 2, CT= TiAlN-TiN	0,201	0,118	–41,293
2*14	MD= DM, IN= 2, CT=TiAlN	0,193	0,422	118,652
3*15	MD= UM, IN= 4, CT= TiAlN-TiN	0,345	0,202	–41,449
4*16	MD= UM, IN= 4, CT= TiAlN	0,318	0,743	133,647
5*9	MD= DM, IN= 4, CT= TiAlN-TiN	0,264	0,180	–31,818
6*10	MD= DM, IN= 4, CT= TiAlN	0,601	0,612	1,830
7*11	MD= UM, IN= 2, CT= TiAlN-TiN	0,158	0,340	115,189
8*12	MD= UM, IN= 2, CT= TiAlN	0,503	0,178	–64,612
	Average	0,322	0,349	23,760

b) The contribution of milling direction

Test No.	Test conditions	*Ra* obtained down milling, (µm)	*Ra* obtained up milling, (µm)	Contribution to improvement at *Ra* average (%)
1*7	v = 50 m/min, IN= 2, CT= TiAlN-TiN	0,201	0,158	–21,393
2*8	v = 50 m/min, IN= 2, CT= TiAlN	0,193	0,503	160,621
3*5	v = 50 m/min, IN= 4, CT= TiAlN-TiN	0,345	0,264	–23,478
4*6	v = 50 m/min, IN= 4, CT= TiAlN	0,318	0,601	88,993
9*15	v = 100 m/min, IN= 4, CT= TiAlN-TiN	0,180	0,202	12,222
10*16	v = 100 m/min, IN= 4, CT= TiAlN	0,612	0,743	21,405
11*13	v = 100 m/min, IN= 2, CT= TiAlN-TiN	0,340	0,118	–65,294
12*14	v = 100 m/min, IN= 2, CT= TiAlN	0,178	0,422	137,078
	Average	0,295	0,376	38,760

c) The contribution of number of insert

Test No.	Test conditions	*Ra* obtained 2 inserts, (µm)	*Ra* obtained 4 inserts, (µm)	Contribution to improvement at *Ra* average (%)
1*5	v = 50 m/min, MD= DM, CT= TiAlN-TiN	0,201	0,264	31,343
2*6	v = 50 m/min, MD= DM, CT= TiAlN	0,193	0,601	211,398
3*7	v = 50 m/min, MD= UM, CT= TiAlN-TiN	0,345	0,158	–54,202
4*8	v = 50 m/min, MD= UM, CT= TiAlN	0,318	0,503	58,176
9*13	v = 100 m/min, MD= DM, CT= TiAlN-TiN	0,180	0,118	–34,444
10*14	v = 100 m/min, MD= DM, CT= TiAlN	0,612	0,422	–31,045
11*15	v = 100 m/min, MD= UM, CT= TiAlN-TiN	0,340	0,202	–40,588
12*16	v = 100 m/min, MD= UM, CT= TiAlN	0,178	0,743	317,415
	Average	0,295	0,376	57,250

d) The contribution of cutting tool

Test No.	Test conditions	*Ra* obtained TiAlN-TiN tool, (μm)	*Ra* obtained TiAlN tool, (μm)	Contribution to improvement at *Ra* average (%)
1*2	v = 50 m/min, MD= DM, IN= 2	0,201	0,193	–3,980
3*4	v = 50 m/min, MD= UM, IN= 4	0,345	0,318	–7,826
5*6	v = 50 m/min, MD= DM, IN= 4	0,264	0,601	127,651
7*8	v = 50 m/min, MD= UM, IN= 2	0,158	0,503	218,354
9*10	v = 100 m/min, MD= DM, IN= 4	0,180	0,612	240,000
11*12	v = 100 m/min, MD= UM, IN= 2	0,340	0,178	–47,647
13*14	v = 100 m/min, MD= DM, IN= 2	0,118	0,422	257,627
15*16	v = 100 m/min, MD= UM, IN= 4	0,202	0,743	267,821
	Average	0,226	0,446	131,500

The numerical results given in Tab. 3 verify the main-effect graphics in Fig. 9, which shows the effects of the control factors on the surface roughness. This table also gives the *Ra* values that can be obtained at different levels of control factors.

4 Conclusions

Machinability experiments were carried out to determine the effects of cutting speed, milling direction, number of inserts and cutting tool coating material on tool life and surface roughness during milling of nickel based superalloy Inconel 718 with coated carbide tools at constant cutting depth and feed rate at the CNC vertical machining center.

At the end of tool life tests:

- The effect of the cutting speed on tool life was higher than the effect of milling method and number of inserts.
- Tool life decreased depending on the increase in cutting speed.
- At both low and high cutting speeds, longer tool life was obtained with down milling method compared to up milling.
- In the up milling with 2 inserts, a 4,4 times higher machining duration was obtained with respect to milling with 4 inserts. However, in the milling of higher speeds longer tool life was obtained with 4 inserts.
- In the milling at v = 50 m/min cutting speed, TiAlN-TiN coated tools exhibited twice as longer tool life compared to TiAlN coated tools.
- The effective wear for both of the milling methods was free surface wear and nose wear. Wear increased linearly in both of the milling methods depending on the cutting time.
- A non-uniform flank wear was formed after down milling and this non-uniform structure increased with the increasing of cutting speed.
- Due to the high temperature generated during the high-speed cutting, molten workpiece diffused into the area where the cutting depth terminated.
- The contributions of TiN layer to the performance of the cutting tool for up milling operations were insufficient in the formation of increasing and irregular tool wear.
- In the milling with 2 inserts a non-uniform flank wear was obtained and bulky chippings occurred towards the nose region of the cutting tool. The flank wear combined with the nose wear due to the effect of the high cutting speed and the nose of the tool got worn and melted.
- While a uniform flank wear was being obtained by machining with 4 inserts at a low cutting speed, the workpiece adhered to the cutting area at the point where the chip depth terminated. A uniform flank wear was obtained at a higher cutting speed as well but the depths and widths of wear tracks increased. Besides, the workpiece diffused into the area where the chip depth terminated.

At the end of the surface roughness tests:

- The most effective control factors on the surface roughness parameter *Ra* were cutting tool coating material, number of cutting tool inserts, the milling direction and the cutting speed accordingly.
- To obtain the lowest *Ra* surface roughness values a down milling must be made at v = 50 m/min cutting speed using TiAlN-TiN coated carbides and binding 2 inserts to the milling holder.

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